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Yield stability and physicochemical characteristics of grain of corn hybrids in High Valleys of Mexico

María Gricelda Vázquez-Carrillo[1]
Aarón Martínez-Gutiérrez[2]
Benjamín Zamudio-González[1§]
Alejandro Espinosa-Calderón[1]
Margarita Tadeo-Robledo[3]
Antonio Turrent Fernández[1]

[1]Valley of Mexico Experimental Field-INIFAP. Los Reyes-Texcoco highway km 13.5, Coatlinchan, Texcoco, State of Mexico. CP. 56250. (gricelda-vazquez@yahoo.com; espinoale@yahoo.com.mx; aturrent37@yahoo.com.mx). [2]Division of Postgraduate Studies and Research-Technological Institute of the Valley of Oaxaca (ITVO). (aaron-0715@hotmail.com). [3]Faculty of Higher Studies Cuautitlán-National Autonomous University of Mexico. (tadeorobledo@yahoo.com.mx).

[§]Corresponding author: bzamudiog@yahoo.com.mx.

Abstract

Corn grain crops in High Valleys of Mexico generally do not meet quality requirements for use in the tortilla and dough industry. New hybrids have been released by research centers for these agroecological conditions and it is necessary to evaluate the stability of production and grain quality in different production environments to avoid rejection in the market. The objective of this study was to identify stable hybrids in their yield, physical-chemical characteristics of the grains and quality of tortillas. Ten hybrids were evaluated in five different environments with four replications for each treatment. The data were analyzed with SAS, version 9.0, the Anova was developed and the comparison of means was made with the Tukey test at 5%. Significant differences were detected for hybrids, environment and hybrid∗environment interaction; for grain yield, physical-chemical variables of the tortillas. The grain yields ranged from 9 to 12.4 t ha^{-1}. The highest stability due to adaptability and yield by environments was found for hybrids H-70, H-66 and Tsiri Puma. Within the group of hard grains are the Tsiri Puma and the commercial control Albatros. The Atziri Puma hybrids, in Temascalcingo and H-50 in Atlacomulco, presented the largest grains. Correlations were found between proteins *vs* oil (r= 0.6), oil *vs* starch (r= -0.86) and proteins *vs* starch (r= -0.82). The highest dough yield was found in the H-51 AE hybrid, followed by H-47 AE, Albatros and Tsiri Puma with 2 kg of dough for each kg of nixtamalized corn. The yield and quality of tortillas of the hybrids evaluated comply with the values demanded by the industry. The results of this research allow us to recommend these new hybrids, due to their stability in yield, in the test environments, commercial quality of the grain and quality of their tortillas.

Keywords: hybrids and flotation index, hybrid-environment, starch.

Reception date: June 2020
Acceptance date: October 2020

Introduction

In Mexico, corn (*Zea mays* L.) is the most important crop in the Mexican diet, mainly as tortillas. In the High Valleys region of Mexico (> 2 200 m), more than two million hectares of corn are planted under 'irrigation tip' conditions, residual or temporary humidity, which represent about 25% of the national surface (SIAP, 2018). The sown maize corresponds mainly to native maize (80%) with low average yield (< 3.14 t ha^{-1}) and improved varieties whose grains do not meet the minimum requirements for use in the dough and tortilla industry (Vázquez *et al*., 2016), turning gray, which limits the acceptance of the product by the consumer (Salinas *et al*., 2012).

Studies of the quality of the grain of new corn hybrids released in High Valleys are required, which satisfy the requirements of the dough and tortilla industry (Gaytan *et al*., 2013) and which help the producers of this region to position its production of corn grain in the tortilla-dough industries (IMT) and that of nixtamalized flour (IHN). The yield and the physical and chemical properties of the corn grain are influenced by the hybrid factor (G), environment (A) and the G×A interaction. Vázquez *et al*. (2016); Lozano *et al*. (2015) evaluated different hybrids to know their adaptability and stability in yield, the physicochemical characteristics of the grain and the quality of the tortilla under contrasting environmental conditions. According to Vázquez *et al*. (2016) for the dough and tortilla industrialists it is important that the hybrids maintain their stability in the yield and quality of the grain in the different production environments avoiding adjustments in the processing.

Among several procedures to estimate the effect of hybrid, environment, and hybrid environment interaction (IGA), the methodology of site regression analysis (SREG) has proven to be successful (Crossa *et al*., 2015), which allows estimating stability, evaluate localities and classify environments through a two-dimensional graph (biplot) of hybrids and environments (Lozano *et al*., 2015). The identification of improved varieties that present stability of yields and better quality parameters of grain and its tortillas, contributes to a greater acceptance by farmers and the industry. The objective of this study was to identify stable hybrids in their yield, physicochemical characteristics of their grains and quality of tortillas among ten corn hybrids evaluated in five environments of the High Valleys of the State of Mexico.

Materials and methods

This work was carried out in the spring-summer 2016 agricultural cycle in five locations in the State of Mexico, namely, by site and sowing date: Temascalcingo (TEM) on May 3; Atlacomulco (ATL) on April 5; Jocotitlan (JOC) on April 13; Ixtlahuaca (IXT) on April 23; and in Jilotepec (JIL), on May 25. The environmental and physicochemical characteristics of the soil of the localities are found in Martínez *et al*. (2018).

Seven hybrids formed by the National Institute of Forestry, Agricultural and Livestock Research (INIFAP) were evaluated: H-66, H-70, H-50, H-47AE, H-49AE, H-51AE and H-53AE; two hybrids, by the Faculty of Higher Studies of Cuautitlan (FESC-UNAM): Atziri-Puma (ATZ) and Tsiri-Puma (TP), both male-sterile version; and a witness: Albatros (ALB), for commercial use by producers from High Valleys.

Soil fertilization was 250-60-60 of NPK + micronutrient mixture in two stages. At sowing, it was fertilized with 100-60-40 of NPK and the rest of nitrogen (150 N) was applied between stage V4-10, divided into equal parts depending on the soil moisture. The design of the treatments was formed by combining the factorial of five environments × 10 hybrids, with four repetitions, considering hybrids, environments and their interactions as sources of variation.

Yield and physical-chemical characteristics of the grain

The yield of the dry weight of grain (RG) was calculated (t ha^{-1}), adjusted to 14% of humidity and extrapolated by one hectare. In the laboratory, a flotation index (IF, indirect measure of hardness) (SE, 2002), weight of 100 grains (PCG) (indirect measure of size) and hectoliter weight (PH) (Salinas and Vazquez, 2006) were measured. Oil (ACE), protein (PRO) and starch (ALM) were quantified according to methods 30-25.01, 46-16.01 and 76-13.01 of AACCI (2000).

Nixtamalization and tortilla making

The nixtamalization process consisted of cooking a 500 g sample of corn, with 3.5 g of $Ca(OH)_2$ and 1 L of water. The cooking time was assigned according to its hardness: IF= 0-12 (Very hard), 45 min; 13-37 (Hard), 40 min; 38-62 (Medium), 35 min; 63-87 (Soft), 30 min; 87-100 (Very soft), 25 min (SE, 2002). The nixtamal rested in the cooking solution (nejayote) for 18 h, and was subsequently washed with water (0.5 L). In the nejayote, loss of dry matter (PMS) was quantified. In a Fudough® Mod. MN-80 Universal stone mill (Fudough S.A., Mex.), the nixtamal was ground with water (5% volume/weight), to obtain the dough (Vázquez *et al*., 2012). The dough was conditioned until a 10 g ±0.02 sphere compressed for 5 s with a 2.5 kg capacity scale reached a diameter of 5 cm, that is, 58% ±0.05 humidity. The dough was die-cut to obtain tortillas 12 cm in diameter and 1.25 mm thick, which were cooked for 1.5 min in a Villamex® Mod. V-14 C/R tortilla maker (Villamex, Mex.) with 3 comales (average temperature = 265 °C).

Once the tortillas were cold (25 °C), they were packed in hermetically sealed polyethylene bags. With the registered weights of nixtamal, conditioned dough and cold tortillas, the yields were calculated. In the freshly made tortillas (30 min) (RE), of 24 (HT24) and 48 (HT48) hours of storage at 4 °C, humidity (AACC, 2000), breaking force (FZA) and maximum elongation (EL) with a Brookfield® CT3 (Middleboro, EU) texturometer (Vázquez *et al*., 2015) at a feed rate of 1 mm s^{-1}. With FZA and EL, Young's modulus of elasticity (Y) (Mao *et al*., 2002) was calculated with the equation Y= E/D, where the stress E= FZA∗cross-sectional $area^{-1}$ of the tortilla disk; D= diameter of the tortilla used for evaluation∗EL^{-1}.

Statistical analysis

An analysis of variance (Anova) was performed, where HIB= fixed effect, AMB= random and the HIB × AMB interaction; tests ($p< 0.05$) of comparison of means (Tukey) and correlation analysis (Pearson). The variables with significant interaction (HIB × AMB), the SREG biplot was obtained in which the main effects of hybrid (CP1) and those of interaction (CP2) were plotted (Vázquez *et al*., 2016; Crossa *et al*., 2015; Lozano *et al*., 2015) with the use of the statistical package Statistical Analysis System (SAS) version 9.0 (SAS Inst., 2002).

Results and discussion

The combined analysis of variance detected significant differences for the hybrid factor, environment and the hybrid-environment interaction (IGA) ($p\leq 0.05$), in grain yield, physical variables (PH, PCG and IF), chemical characteristics (ACEI, PROT, ALM) (Table 1) and tortillas (HT, HT24, HT48, FZAHT, FZA24, FZA48, YRE, Y24, Y48). The average yield of the hybrids was higher than the annual average (irrigation + temporary) state (4.3 t ha^{-1}) and national (3.9 t ha^{-1}) (SIAP, 2018). The PH exceeded the defendant in the NMX-032/1 standard (SE, 2002), with a minimum density of 74 kg hL^{-1}, with hard and intermediate endosperm (IF between 13-37 and 38-62 respectively). The contents of ACE, PRO and ALM are within the range reported for serrated corn (Watson, 2003). Th e Atziri Puma hybrid was the one with the highest RG, PCG and PRO, but the one with the lowest content of ALM (Table 1).

Table 1. Average yield values, physical and chemical characteristics of grain of ten corn hybrids evaluated in five environments of the High Valleys of the State of Mexico. Spring-summer 2016.

Hybrids	RG (t ha^{-1})	PH (kg hL^{-1})	PCG (g)	IF	Oil§	Protein§ (%)	Starch§
H-51AE	10.4 d	77.6 e	36.1 h	62 a	5.1 cd	10.1 bc	69.6 bcd
H-47AE	11.2 c	77.3 f	36.1 h	60 a	4.9 e	9.9 d	70 a
H-66	11.6 abc	77.2 f	37.9 f	54 b	5.4 a	9.8 d	69.5 cd
Atziri Puma	12 a	77.2 f	39.9 a	51 bc	5.3 ab	10.3 a	69.1 e
H-50	11.5 abc	77.5 e	39.2 b	49 bcd	5.1 cd	10.2 ab	69.4 de
H-70	11.6 abc	78.4 d	38.7 c	48 cde	5.2 bc	9.9 d	69.4 de
H-53AE	10 d	78.7 c	38 e	44 de	5 d	10.2 a	69.8 abc
H-49AE	10.5 d	79.1 b	36.1 h	43 e	4.9 e	10.1 c	69.9 ab
Tsiri Puma	11.8 ab	79.3 a	38.6 d	37 f	5.3 ab	10.2 a	69.1 e
Albatros	11.4 bc	79.3 ab	37.3 g	35 f	5.1 d	9.8 d	69.9 ab
Means	11.2	78.2	37.7	48.3	5.1	10	69.6
DSH$^{£}$	0.53	0.18	0.12	5.28	0.13	0.13	0.36

Means with the same letter in the column are statistically equal (Tukey, 0.05); DSH= honest significant difference; RG= grain yield; PH= hectoliter weight; PCG= weight of 100 grains; IF= float index: §= reported on a dry basis.

The significance of IGA indicates that the hybrids evaluated presented different responses or adaptation in some specific environment. For yield, the first two components of SREG explained 82.7% (CP1 59.5% and CP2 23.2%) of the variability due to the interaction (Figure 1A). Crossa (1990) mentions that the value higher than 75% of CP is acceptable to be considered a reliable interpretation of hybrid-environment. The results are consistent with the findings of other researchers (Vázquez *et al*., 2012; Lozano *et al*., 2015). The long length of the ambient vector implies a greater difference in yield between HIB (Crossa *et al*., 2013).

The most distant environments were TEM and ATL, while the vectors closest to the origin corresponded to Jocotitlan, Jilotepec and Ixtlahuaca. In the TEM locality, the highest variability between HIB (> vector log) and the highest yield was recorded. In the macro environment made up of TEM, JIL and IXT, the Atziri Puma hybrid stood out as it registered the highest yield, followed by the H-66 and H-50 hybrids (Figure 1A) with better yields.

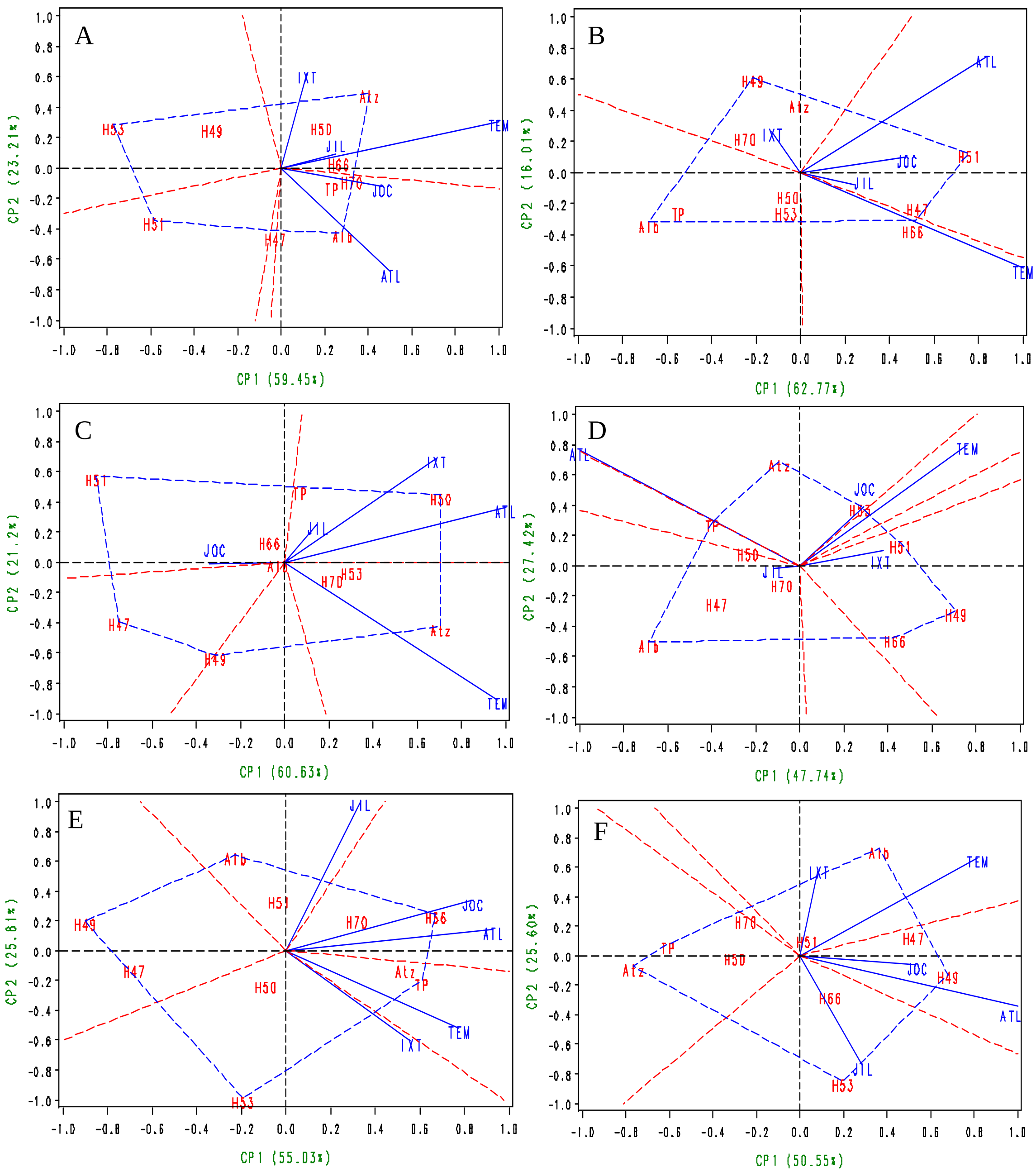

Figure 1. SREG biplot graphs for grain yield variables (A); flotation index (B); weight of one hundred grains (C); percentage of starch (D); oil (E); and protein (F).

The yields ranged from 9 to 12.4 t ha^{-1} (Table 1). The hybrids H-70, H-66 and Tsiri Puma adapted better due to the fact that they present the CP1 value closer to the zero origin (Vázquez *et al*., 2016), therefore, they present greater stability in all test environments; in parallel, those farthest away showed greater variation in their behavior (Crossa *et al*., 2015). According to Crossa *et al*. (2013), from the point of view of a breeder, the best hybrids are those with PC2 values close to zero and high PC1 values. In this case, the hybrids H-66, H-70 and Tsiri Puma present these attributes, with adaptability and yield stability for recommendation in other areas of the High Valleys of the State of Mexico.

In the second macro environment (ATL and JOC), the Albatros hybrid obtained the best yields, followed by Tsiri Puma and H-70 with average yields of 11.8 and 11.6 t ha^{-1} respectively. Despite the positive response of Albatross in this macro environment, specifically in ATL, low yields (9 t ha^{-1}) were observed, compared to the other environments. Response that is attributed to the low investment in fertilization and phytosanitary control (Martínez *et al*., 2018), which affected the vigor of the plants and grain yield.

Physical characteristics

The IF was explained in 78.8% by the first two CP. Figure 2B shows in ascending order, from left to right, the number of floating grains; that is, inverse of hardness. According to the hardness classification by the IF (SE, 2002), the hardness of the hybrids was from intermediate to hard (IF). The dough and tortilla industry (IMT) prefer corn with IF $\leq$ 40 and that of nixtamalized flour (IHN) with less than 20 floating grains (Gaytan *et al*., 2013). The preference grows to the left of the biplot, with lower IF (Figure 1B). The hybrids evaluated presented IF between 15-50, which are suitable for the dough and tortilla industry IMT, absorb more water during nixtamalization and rest, the above, is related to a higher yield of dough and tortilla (Vázquez *et al*., 2015).

Within the group of hard grains are Tsiri Puma and Albatross (Table 1), the rest correspond to grains of intermediate hardness. Hard grain hybrids (Tsiri Puma and Albatros) are associated with higher yields, which coincides with what was reported by Vázquez *et al*. (2012), that the harder the grain, the higher its RG, PH and lower IF. These hybrids can be recommended for the nixtamalized flours industry (IHN), as they achieve less hydration during cooking, facilitating their grinding (Salinas *et al*., 2012).

The hybrid H-51 AE corresponds to the one with the highest stability in the IF (Figure 1B) considering the criteria mentioned by Crossa *et al*. (2013) in the PC and in Jocotitlan presented the softest grains. The hybrids Albatros and Tsiri Puma responded positively to adaptability in ATL and JOC, while the hybrid H-49 AE in TEM.

In the IF biplot it is observed that in TEM and ATL there was greater variability between the HIB, so the results obtained in the two environments are more reliable in relation to the other production environments, although they present a greater effect on the IGA than in JOC, where they appear near the X axis. Yan *et al*. (2007) explain that, the greater the relative dispersion of the AMB, with respect to the horizontal axis, the representativeness of this in the analysis is reduced, since there is a greater effect of IGA in the variable. JIL and IXT did not discriminate between hybrids, given their proximity to the origin (shorter vector). Yan *et al*. (2007) point out that environments that present an angle less than 90° classify hybrids in a similar way, a similar case is shown in these two environments (Figure 1B).

The PH had a behavior similar to IF, registering the best response in the hybrids Atziri Puma and Albatros (79.3 kg hL^{-1}), followed by the hybrid H-49 AE (79.1 kg hL^{-1}). The hybrids that presented the lowest PH were H-47 AE, Atziri Puma and H-66 (Table 1). In all the hybrids evaluated, a value higher than that required by the NMX-032/1 (SE, 2002) of 74 kg hL^{-1} was found. These results exceed those reported by Vázquez *et al*. (2016) when evaluating the stability of the yield and the physical variables of the grain, as well as for nixtamal and tortilla of eleven corn hybrids in six environments in the central region of High Valleys of México.

In the grain size, represented by the weight of one hundred grains (PCG) is a common variable in the choice of grains to process. The first two PC were significant and represented 81.83% of the variability of the data (Figure 1C). The standard (NMX-034/1 2002) did not consider the size of the grain; however, it is a variable of interest that impacts cooking and water absorption during nixtamalization (Antuna *et al*., 2008).

Considering the classification of Salinas and Vázquez (2006), the large grains present PCG > 38 g, the intermediate grains a PCG of 33 to 38 g and the small grains PCG <33 g. The hybrids Atziri Puma in TEM and H-50 in ATL presented the largest grains (Figure 1C). However, according to the selection criteria of Salinas and Aguilar (2010), the tortilla-dough and nixtamalized flour industries prefer small and medium grains. When extending the environmental vectors towards their negative side, a high correlation was found between H-51AE in TEM, as well as between H-47AE in IXT and ATL, which shows a specific adaptation to these environments, with small grains (Figure 1C).

The IHN prefers intermediate-size corn, while IMT prefers intermediate and small grains, due to the better hydration that favors the yield of nixtamal, dough, and tortilla as they present high humidity (Salinas and Aguilar, 2010). Under this premise, seven of the ten hybrids evaluated presented intermediate size, resulting in an alternative with adequate characteristics for processing for IMT industries.

Chemical characteristics

There are significant differences ($p< 0.05$), for HIB, AMB and interaction between the two factors was detected in the variables evaluated, a correlation was observed between PROT vs ACEI (r= 0.60, $p\leq 0.01$), ACEI vs ALM (r= -0.86, $p\leq 0.01$) and PROT vs ALM (r= -0.82, $p\leq 0.01$), which confirms what was reported by Vázquez *et al*. (2015) and it is visible in the biplot, since they are similar or 'quasi-symmetric' with each other.

The most important compound of the corn grain is starch, since it represents ¾ parts of the total (Paredes *et al*., 2009). In this study, ALM percentages (69-70%) were found with a minimal difference between the hybrids. These values are consistent with that reported for serrated type maize (Watson, 2003). The hybrid H-49 AE was better adapted, in relation to the other hybrids and with a higher percentage of starch, followed by H-47 AE, H-53 AE and Albatros, while the Atziri Puma and Tsiri Puma presented values lower than 69.1, respectively (Table 1).

The hybrids stand out in their ACE content, the lowest percentages were 4.88 and 4.90% (Table 1), higher than that observed in hybrids of normal endosperm by Vázquez *et al*. (2015). The highest percentages of ACE were found in larger grains (r= 0.43, $p\leq 0.01$). According to Vazquez *et al*. (2015), are considered hybrids with high oil content (ACA) when they have more than 5% in the grain. Within this classification, the HIB tested in this experiment can be located, which is relevant in the preparation of tortillas by IMT, due to the relationship between the ACE in grain and the softness of the resulting tortillas (Vázquez *et al*., 2016), a greater amount of it reduces the retrogradation of starches (Putseys *et al*., 2010).

Therefore, the presence of oil in the corn kernel can significantly improve the firmness and chewing of the tortilla (Vidal-Quintanar *et al*., 2001). In JOC and ATL, grains with a higher percentage of oil were produced. The hybrids with high percentage of oil in grain were H-66, Atziri Puma, and Tsiri Puma, these last two are stable in TEM. The hybrids with the lowest percentage were H-49 AE and H-47 AE with 4.9% respectively (Figure 1E).

In protein, between 9.75 and 10.31% were obtained (Table 1), the highest percentages in H-53 AE, Tsiri Puma and Atziri Puma (≥10.22%), while the lowest was obtained in the Albatros hybrid. The results are similar to those reported by Vázquez *et al*. (2012) who observed from 9.76 to 12.54% protein in local varieties and in improved hybrids from 8.24 to 11.34%. These variations in proteins are associated with the genetics of the materials tested.

Quality nixtamal-tortillas

There were significant differences ($p< 0.05$) between the hybrids, environments and in IGA for the quality variables of nixtamal, dough and tortillas. The assignment of cooking times according to the IF allowed to reach humidity in the nixtamal between 45.6% (intermediate) and 47.3% (hard), values that in dough increased from 57.4 and 58.1% (Table 2), an increase that is due to, in hard corns, the longer cooking time, and in the dough to the addition of water during grinding and to condition it, prior to stamping.

Table 2. Average values of quality variables of nixtamal, dough and tortillas of 10 corn hybrids tested in 5 environments of the High Valleys of the State of Mexico. Spring-summer 2016.

Hybrids	Humidity (%)					Lost dry material (%)	Yield (kg kg^{-1} grain)		
	Nixtamal	Dough	Tortillas				Nixtamal	Dough	Cold tortilla
			Current	24 h	48 h				
H-51AE	46.9 b	58.1 a	44.2 ab	45.3 abc	44.8 cde	3.35 ef	1.89 c	2.01 a	1.55 a
H-47AE	46.1 d	57.8 ab	44.7 a	45 bcde	44.8 bcde	3.46 cd	1.88 d	2 abc	1.57 a
H-66	46.5 c	57.7 abc	45.1 a	45.3 abcd	45.4 ab	3.54 c	1.9 a	1.99 bcde	1.56 a
ATZ	46.1 d	57.5 bc	44.9 a	44.7 de	44.5 def	3.28 f	1.87 f	1.99 bcde	1.57 a
H-50	45.7 ef	57.5 bc	44.7 a	44.9 bcde	44.5 def	3.34 ef	1.85 j	1.99 cde	1.52 a
H-70	45.6 f	57.4 c	43.5 b	44.6 e	44.1 f	3.38 de	1.87 g	1.98 e	1.52 a
H-53AE	45.6 f	57.6 bc	44.6 a	44.8 cde	44.9 bcd	3.48 c	1.85 i	1.98 de	1.55 a
H-49AE	46 de	58 a	44.7 a	45.7 a	45.5 a	3.94 a	1.87 h	1.99 bcde	1.54 a
TP	46.4 c	58.1 a	44.9 a	45.4 ab	45.1 abc	3.73 b	1.89 b	2 abcd	1.55 a
ALB	47.3 a	57.9 a	44.4 ab	45.2 bcde	44.3 ef	3.53 c	1.88 e	2.01 ab	1.53 a
DSH	0.28	0.35	1.08	0.57	0.56	0.08	0.01	0.02	0.07

Means with the same lowercase letter in the column are statistically the same (Tukey, 0.05). £: DSH, honest significant difference.

The highest dough yield was found in H-51 AE, followed by H-47 AE, Albatros and Tsiri Puma with 2 kg of dough for each kg of nixtamalized corn. The yield of nixtamal and dough was similar to that reported by Gaytan *et al*. (2013); Vázquez *et al*. (2015); Vázquez *et al*. (2016). While the humidity in freshly made tortillas (30 min) was 43.5 to 45.1% (Table 2). The JOC locality showed the highest diversity in the 30 min HT between hybrids, the hybrids H-51 AE and Atziri Puma were the most stable in the 30 min HT.

The stored HT (24 and 48 h) was slightly higher than the newly prepared, in the hybrids (Table 2). In TEM the hybrids Tsiri Puma, Albatros and H-53 AE presented high percentages of humidity, and the lowest in the hybrid H-50 (Table 2). In all the hybrids, the tortilla yield was higher than the 1.5 kg of tortilla per kg of corn grain demanded by the industrial tortilla-dough (Salinas and Aguilar 2010). By environment, the lowest average yield was observed in Jilotepec with 1.51 kg of tortilla per kg of corn grain. While the H-70 hybrid presented lower values and the lowest in JOC, although it is mostly adapted to JIL.

In the loss of dry matter (PMS), all the materials registered values lower than the 5 g 100 g^{-1} declared in the -034(1) standard (SE, 2002) (Table 2). The results coincide with that reported by Vázquez *et al*. (2015), where the mean PMS was 3.31 g 100 g^{-1}, for six hybrids) from High Valleys of México.

Tortilla consumers demand that they be soft and flexible (Mao *et al*., 2002). Most of the texture variables showed a significant difference (p> 0.01) due to the effect of the genotype, the environment and the IGA, the results shown include the averages of the five locations. The freshly made tortillas showed greater variability, with respect to the stored ones (Figure 1).

At 30 min after making the softest tortillas, they were the hybrids H-47E, H-53AE and H-49AE, which required less force to break (x= 1.4 N), had a good elongation (EL) (x= 8.3 mm) and their modulus of elasticity (Y) was the lowest (x= 11.8 N cm^{-2}), this quality of the tortillas can also be related to their oil content (± 5%), as reported by Vázquez *et al*. (2015). The next group included H-51AE, H-66, H-50 and Tsiri-Puma, whose tortillas required 1.56 N to break, the Y increased (x= 12.4 N cm^{-2}) in proportion to the increase in FZA, since its EL was equal to that of group 1 (8.3 mm) (Figure 3).

(A) (B)

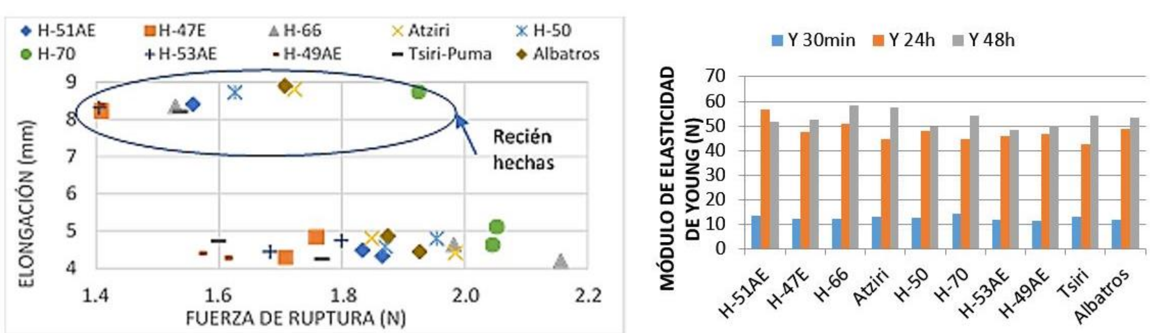

Figure 3. Breaking force and elongation (A) and Young's modulus of elasticity (B) in freshly made and stored tortillas (24 and 48 h). Averages of the five locations.

The loss of flexibility of the tortillas upon cooling (24 and 48 h in refrigeration) is due to the formation of a rigid structure caused by the retrogradation of starch and the association with proteins, fiber and other chemical components (Agama-Acevedo *et al*., 2011). The greatest increase in FZA occurred at 24 h, this was of the order of 0.28 N (18%), while at 48 h of storage in some tortillas the FZA was reduced, in others it remained the same and only in three genotypes H-66, Atsiri-Puma and Tziri-Puma increased the FZA. Similar behavior was observed in the Y. The elongation of the stored tortillas did not show statistical difference due to the effect of the storage time, the values were 4.3-5.1 mm (24 h) and 4.2-4.6 mm (48 h).

The best tortillas with 24 h of storage were from the H-49AE hybrid, these required less force to break (x= 1.6 N), their EL was 4.4 mm and their Y was 46.8 N cm^{-2} (Figure 3 A and B). The good quality of the stored tortillas could be explained by the oil content of these corn (±5%). In this regard, it has been reported (Vázquez *et al*., 2015) that lipids interact with amylose molecules during nixtamalization, affecting the physicochemical properties of starch and favoring the formation of the amyl-lipid complex, which favors the texture of tortillas (Vázquez *et al*., 2014).

Conclusions

The highest yield and variability between hybrids were recorded in the locality of Temascalcingo. In the macro environment formed by the localities of TEM, JIL and IXT, the highest yield was for the hybrids Atziri Puma, H-66 and H-50, they were the ones with the greatest adaptability and stability, so they can be widely recommended for High Valleys of the State of Mexico. In the second macro environment (ATL and JOC) Tsiri Puma and H-70 stood out with average yields of 11.8 and 11.6 t ha^{-1} respectively. All hybrids complied with the commercial specifications of the NMX-034(1) standard for corn destined for the nixtamalization process.

They are grains of medium to small size, with a hectolitric weight above 74 kg hL^{-1} and intermediate to hard hardness. Its oil content was between 4.9 and 5.4%. The losses of dry matter in the nejayote were within that demanded by the industrialists, while the humidity in nixtamal, dough and tortillas, as well as the yields were high. The best freshly made tortillas were produced with the male sterile hybrids H-47AE, H-53AE, H-49AE, which were the ones with the lowest yield (x= 10.5 t ha^{-1}). The results of this research allow us to recommend these new hybrids, due to their stability in yield, in the test environments, commercial quality of the grain and quality of their tortillas.

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